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Several Ways to Leave for Luna

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SEVERAL WAYS TO LEAVE FOR LUNA*

Theodore H. Sweetser, Ph. D.+

This paper is a comprehensive survey of ballistic trajectory designs leading to the delivery of small spacecraft to the surface of the Moon. All of the currently known types of ballistic transfer trajectories are examined (including some new ones): direct, reverse interior AV-hmar gravity assist (RIDL), backflip, weak stability boundary (WSB), interior WSB, and the bounding case which minimizes the post-launch AV. Then different landing strategies are examined and delivered masses are calculated based on the capabilities of two launch vehicles: Taurus with a STAR 37XFP upper stage and a Med-lite.

INTRODUCTION

As the poet could have said:

There are half a dozen ways
A lunar course to lay
And every single one is good for something. ‡

These half-dozen or so classes of lunar transfer trajectories vary in their propellant requirements, flight time, and arrival geometry. The first section of this paper will give an overview of their characteristics. The second section will examine the options available for landing a small spacecraft on the moon and will calculate delivered masses for two launch vehicles — the Taurus (with a STAR 37)(FP upper stage) and the Med-lite. The paper then concludes with suggestions for further work in this area.

LUNAR TRANSFER TRAJECTORIES

Transfer trajectories can be combined with a phasing orbit at the beginning if desired to extend the launch period, and all of them allow

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* The research described in this paper was performed at the Jet Propulsion Laboratory, California . Institute of Technology, under contract with the National Aeronautics and Space Administration.

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‡ Fortunately Kipling knew better and he wrote "in the Neolithic Age" instead.

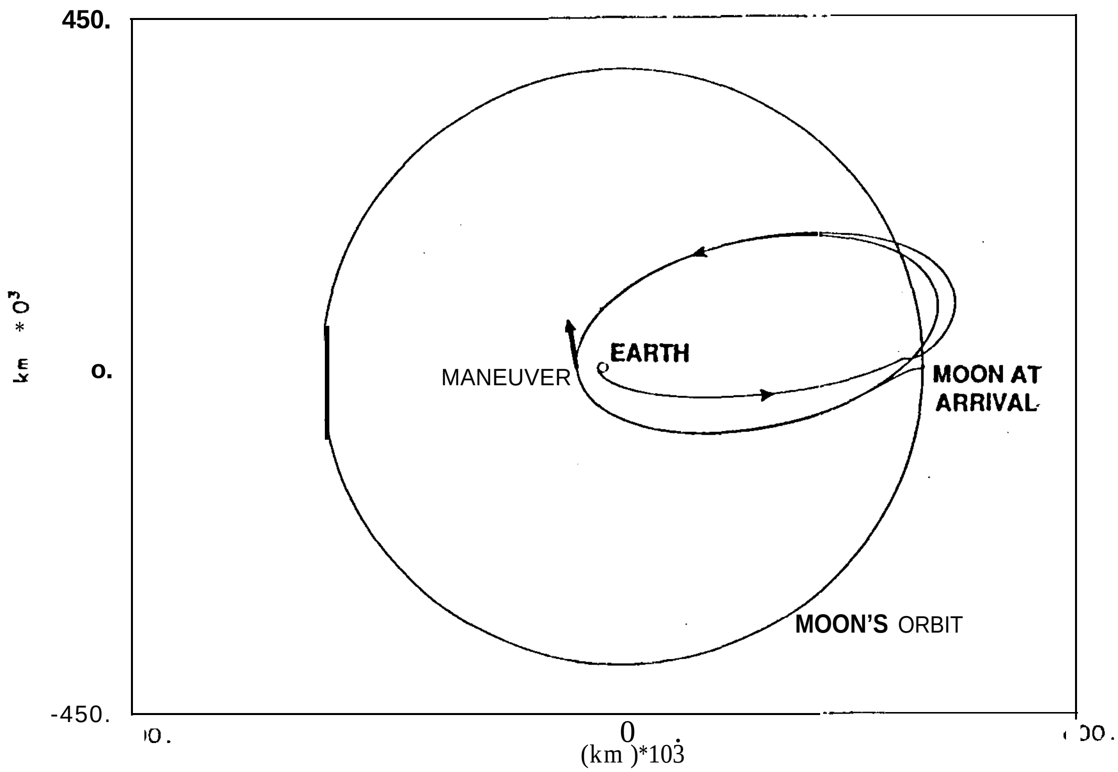

Figure 2. A RIDL Transfer shown in inertial coordinates (Sweetser, 1993a).

capture into a large ellipse to more than 2,5 km/s for a soft landing. For comparison purposes the mission chosen is a landing mission, For a Hohmann transfer with favorable lunar geometry, the arrival V_∞ is 793 m/s resulting in a landing velocity of 2.504 km/s, where the transfer flight time is about five days.

Reverse Interior AV Lunar Gravity Assist (RIDL)

This takes the direct transfer a step further. Instead of staying at the Moon when it is encountered, the spacecraft flies by in a gravity assist which raises its perigee and apogee slightly. Then a small perigee maneuver lowers the apogee to near tangency with the Moon's orbit, resulting in a lower arrival velocity at the Moon and a small overall propellant saving. For example, in the case described by Sweetser (1993a) and shown in Figure 2, there is a total AV reduction of 23 m/s (including a 13 m/s perigee maneuver) compared to the Hohmann transfer. This transfer is a variation on the more familiar ΔV-Earth Gravity Assist (ΔV-EGA) trajectory to the outer planets — it reverses it in that the transfer is towards the flyby body instead of away from it and is interior in that the AV is done inside the flyby body's orbit instead of outside,

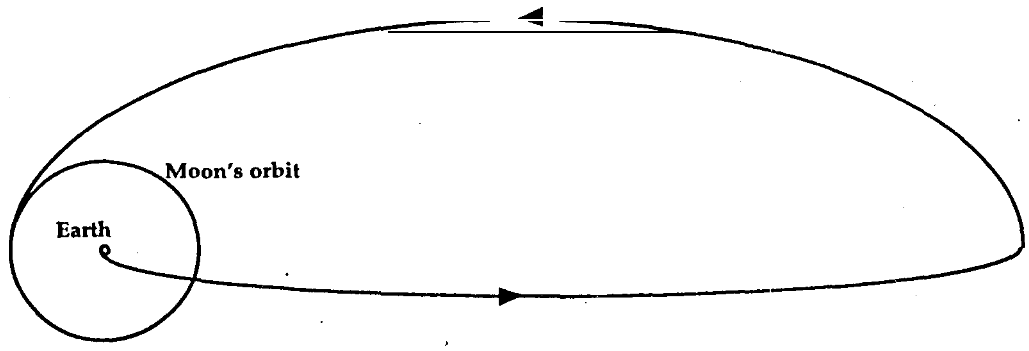

Figure 4. A **bielliptic** transfer from low Earth orbit to the Moon,

radius with a maneuver at apogee, and times everything to encounter the Moon at perigee as shown in Figure 4. In a biparabolic transfer the apogees of the transfer ellipses is pushed to infinity so that they become transfer parabolas and the apogee maneuver goes to zero. Flight times range from a month to infinite in the biparabolic case. In this class of transfer the approach to the Moon tends to be toward the Moon's trailing side, opposite the direct approach. Theoretically, this would reduce the AV needed for the transfer by only 13 m/s at best compared to a Hohmann transfer, but by combining it with an initial lunar gravity assist an additional 45 m/s or so could be saved at injection. In the real world, however, if the apogee is large enough to offer any advantage over the Hohmann transfer then solar perturbations become significant, leading to . . .

Weak Stability Boundary (WSB)

The prototype of the WSB transfer is the Belbruno-Miller transfer (Miller and Belbruno, 1991). It is like the bielliptic transfer but differs in two ways: firstly, the apogee "maneuver" is effected by solar perturbations -- since it has no propellant cost it is done at a lower apogee than would otherwise be optimal so that the lunar arrival velocity is further reduced; secondly, the lunar arrival takes advantage of the Moon's gravity so that the spacecraft is "captured" ballistically, i.e., its osculating eccentricity at periselene is less than one. Belbruno calls this being near the Earth-Moon Weak Stability Boundary.

Yamakawa (1992, 1993) has done the most extensive analysis in categorizing WSB transfers, which differ according to how much time is spent in the intermediate "ellipse", whether one or two revolutions are done in that "ellipse", and where the apogee is relative to the Sun-Earth line. Flight times range from $2\frac{1}{2}$ up to many months, but substantial AV savings are possible, typically around 180 m/s compared to the Hohmann transfer. The final approach to the Moon is from the anti-Earth direction, thus toward the

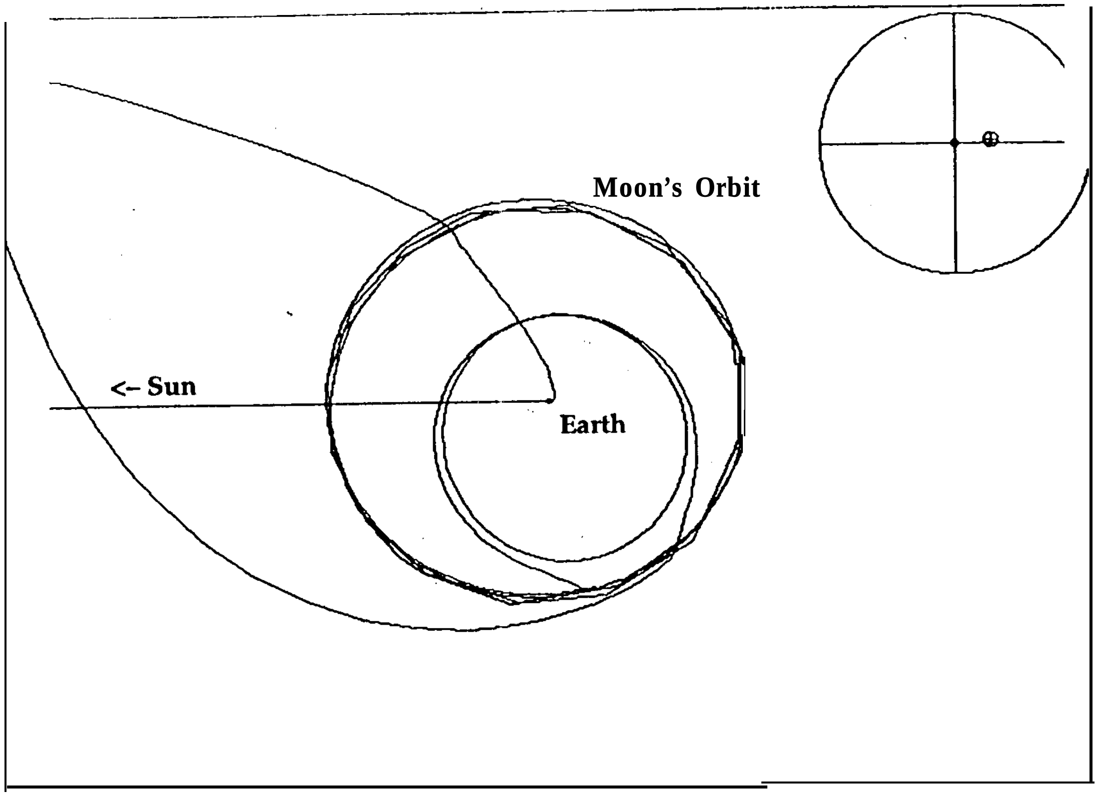

Figure 6. An Interior WSB Transfer, shown in rotating coordinates with the Earth-Sun line fixed. The B-plane diagram in the comer shows the aimpoint of the first lunar flyby.

achieving a ballistic capture, the spacecraft does a more distant flyby which results in the subsequent spacecraft orbit lying entirely inside the Moon's orbit. This interior orbit can be timed so that one or two months later the spacecraft again encounters the Moon in a Weak Stability way that leads to ballistic "capture". The flight time is somewhat more than that of the standard WSB transfer but now the approach to the Moon at arrival is along the Earth line and thus toward the near side of the Moon. See Figure 6. Once again, a lunar gravity assist to gain energy occurs shortly after launch.

AV-Minimizing

Is there any end to this? In the AV sense there is, at least in the circular restricted three-body model. An analysis based on J acobi's constant (Sweetser, 1991) has shown that the total AV absolutely required to go from low Earth orbit to low lunar orbit is about 230 m/s less than for the Hohmann transfer. Using approaches suggested by this analysis, Pernicka et al. (1994) have found transfers which involve a transition from geocentric ellipses to selenocentric ellipses near the intermediate Earth-Moon Lagrange point and which require

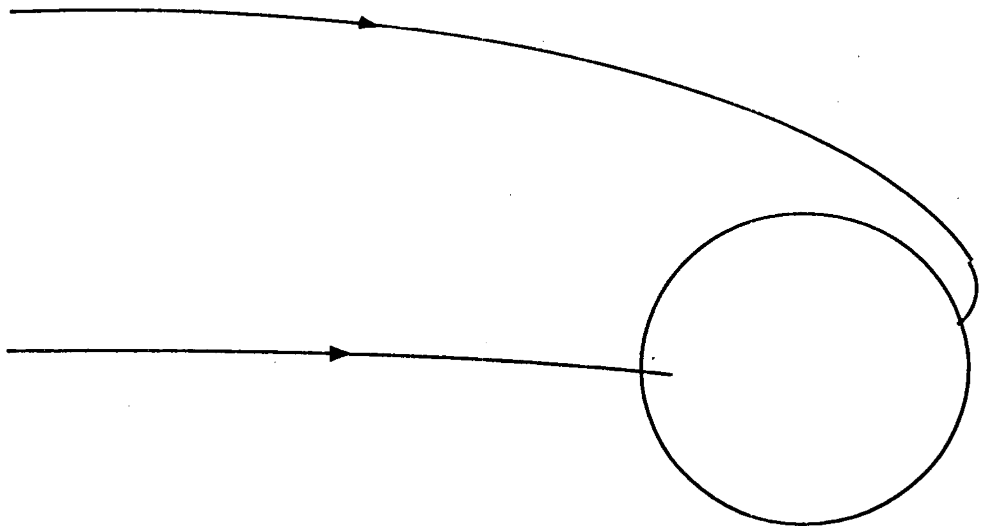

Figure 8. Two alternative landing strategies at lunar approach: go straight in or go into orbit with perilune above the surface on the opposite side and then use rockets to brake to a landing near perilune.

includes 100 m/s for midcourse corrections for all except the AV-minirnizing transfers; since AV-minimizing transfers included multiple revolutions around the Earth after injection they are not as sensitive to injection errors so they are allocated 50 m/s for midcourse corrections.

The use of phasing orbits after injection is required in the cases of the standard and interior WSB transfers if launch periods of more than a few days each month are needed. Another benefit of phasing orbits is that they allow correction of launch energy errors when the spacecraft returns to perigee, where the propellant cost of the correction is minimized. One characteristic of all these lunar transfers is that launch energy correction one day after launch requires several times the “AV of the initial error, a characteristic due to the low C_3 of these transfers.

Table 1 does not include any steering or gravity loss at the lunar arrival. The C_3 and AV required for a transfer depend on the launch and arrival times since the Moon’s orbit is significantly non-circular. The numbers given in Table 1 are for typical cases with comparable arrival dates.

ARRIVAL OPTIONS

The arrival descent strategy is governed by two major choices: firstly, a hardware choice whether to use a solid stage to remove most of the Moon-relative velocity or to rely solely on a liquid propulsion system, and secondly, a trajectory choice whether to descend directly to the surface or to target perilune tens of kilometers above the surface and use the engines to slow down near perilune and land (see Figure 8).

Table 2

LANDED MASSES ON THE MOON FOR SELECTED TRANSFER TRAJECTORIES AND LAUNCH VEHICLES FOR A SURVEYOR-TYPE APPROACH.

(Units used in the table are **km^2/s^2** for **C3, m/s for ΔV, and kg for mass.)**

	Taurus / STAR 37xfp			Med-lite		
	Direct	WSB	Minimizing	Direct	WSB	Minimizing
C3	-2.00	-1.40	-2.90	-2.00	-1.40	-2.90
injected mass	340.0	336.0	347.0	615.0	606.0	628.0
adapter (1%)	3.4	3.4	3.5	6.2	6.1	6.3
net inj. mass	336.6	332.6	343.5	608.8	599.9	621.7
midcrs. det AV	0.0	0.0	70.0	0.0	0.0	70.0'
midcrs. stat AV	100.0	100.0	50.0	100.0	100.0	50.0
midcourse AV	100.0	100.0	120.0	100.0	100.0	120.0
midcrse. prop mas	11.0	10.8	13.4	19.8	19.5	24.2
arrival mass	325.6	321.8	330.1	589.0	580.4	597.5
arrival vel	2504.0	2341.0	2327.0	2504.0	2341.0	2327.0
gravity loss	25.0	23.4	23.3	25.0	23.4	23.3
arrival ΔV	2529.0	2364.4	2350.3	2529.0	2364.4	2350.3
arrival prop mass	192.6	182.5	186.5	348.5	329.1	337.5
solid stage	34.1	33.8	33.9	S2.9	S2.3	52.5
descent mass	98.9	105.5	109.8	187.7	199.0	207.5
descent ΔV	375.0	375.0	375.0	375.0	375.0	375..0
descent prop mass	11.5	12.3	12.8	21.9	23.2	24.2
landed mass	87.4	93.2	96.9	165,8	175.8	183.2
prop subsys mass	20.0	20.0	20.0	20.0	20.0	20.0
net landed mass	67.4	73.2	76.9	145.8	1S5.8	163.2
post launch AV	3004.0	2839.4	2845.3	3004.0	2839.4	2845.3
bipropellant mass	22.5	23.2	26.2	41.7	42.8	48.4
full solid stage	226.7	216.3	220.4	401.3	381.4	390.1

extended STAR 27 or an offloaded STAR 30. The assumptions made in this mass analysis were as follows:

- an adapter for the spacecraft would be connected to the launch vehicle and would take 1°/0 of the injected mass (the performance cost of the Payload Attach Fitting has been included in calculating the capabilities of the launch vehicles)

- the inerts for the solid motor used to brake the arrival would mass 18.3 kg for the STAR 24 and 27.4 kg for the STAR 27 or STAR 30, plus 3% of the propellant mass for an adapter

- safing and arming hardware for the solid motor would be 10 kg for a STAR 24 and 15 kg for a STAR 27 or STAR 30

- the effective Isp for the arrival braking would be 288 s; the Isp for the vernier engines would be 308 s

- gravity and steering loss for a vertical braking descent would be l% of the braking AV

- the AV needed for the final descent is for a high-altitude braking maneuver and is taken from (Surveyor, 1969)

- because the AV requirements are so great, an I_{sp} of 330 s is assumed which is consistent with an advanced liquid propulsion system; an assumption of an I_{sp} of 317s does not increase gravity losses but would require more propellant mass

- the adapter between the spacecraft and the Payload Attach Fitting of the launch vehicle is again taken to be l% of the injected mass.

Other Alternative Landing Scenarios

Two other independent alternatives can be considered for the landing scenario: designing the spacecraft for a hard landing instead of the final controlled descent and using a very high-thrust throttleable liquid propulsion system for the arrival braking. The Russian missions Luna 9 and Luna 10 combined both of these alternatives for their landings: a 45 kN engine was used to brake the main spacecraft sufficiently so that when it hit the surface a small science package could be ejected to make a "hard" landing safely.

If a hard landing is used, the mass of the final radar altimeter and velocity sensors could be eliminated as well as the descent propellant, but sufficient padding for the payload would need to be added to protect it from a landing impact of 50 m/s to 200 m/s. One advantage of the hard landing strategy might be reduced risk, since a failure of the padding is less likely than a failure of the control and propulsion systems used in the final descent, .

A very high-thrust liquid propulsion system would be overkill for the small spacecraft masses considered in this paper.

FURTHER WORK

A number of open questions remain to be answered. We know a solution exists: Luna 9 and Surveyor 1 landed successfully almost 30 years ago." Some questions may reasonably be deferred to detailed study of particular missions, but some answers need to be known earlier in order to match transfer types to mission requirements for preliminary surveys such as this one. In rough order of priority:

What are the geometric constraints on WSB transfers? A qualitative understanding of these transfers has been developed (Yamakawa et al., 1993; Sweetser, 1993b) and has led to the discovery of the interior WSB transfer, but there is no quantitative understanding, at least in this country. Studies need to done to find the cost of varying the approach direction (which may be rather tightly constrained, according to Yamakawa et a 1. (1993)) and the Sun-Moon-spacecraft angle at approach (which is not so tightly constrained).

What are the navigation and maneuver requirements for lunar transfers? Even the direct transfer is not well known in this regard, since Surveyor had a liquid upper stage for its injection, while the launch vehicles

Non-linear Astrodynamics Conference, Minneapolis, MN,., 8-10 November 1993.

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1NTRODUCTION

As the poet could have said:

There are half a dozen ways
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***And** every single one is good for something.* ‡

These half-dozen or so classes of lunar transfer trajectories vary in their propellant requirements, flight time, and arrival geometry. The first section of this paper will give an overview of their characteristics. The second section will examine the options available for landing a small spacecraft on the moon, giving delivered masses for two launch vehicles which are much in favor in today's political climate — the Taurus (with a STAR 37xfp upper stage) and the Med-lite. The paper then concludes with suggestions for further work in this area.

LUNAR TRANSFER TRAJECTORIES

All of these transfer trajectories can be combined with a phasing orbit at the beginning if desired , n ; : tend the launch period, and all of them allow

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class of transfer the approach to the Moon tends to be toward the trailing side, opposite the direct approach. Theoretically, this would reduce the AV needed for the transfer by only 13 m/s at best, but by combining it with an initial lunar gravity assist an additional 45 m/s or so could be saved at injection. In the real world, however, if the apogee is large enough to offer any advantage over the Hohmann transfer then solar perturbations become significant, leading to . . .

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Interior WSB

The standard WSB transfer seems strange enough but the interior WSB transfer trajectory goes one step beyond. In the interior WSB transfer the arrival at the Moon occurs the third time the Moon is encountered. This transfer is initially the same as the standard WSB transfer, but at the second lunar encounter instead of coming close to the Moon and achieving a ballistic capture, the spacecraft does a more distant flyby which results in the subsequent spacecraft orbit lying entirely inside the Moon's orbit. This interior orbit can be timed so that half a month, one month, or two months later the spacecraft again encounters the Moon in a Weak Stability way and gets "captured" ballistically. The flight time is somewhat more than that of the standard WSB transfer but now the approach to the Moon at arrival is toward the near side. See Figure 5. Once again, a lunar gravity assist to gain

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ΔV-Minimizing

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The Various Transfers Summarized

Table 1 summarizes characteristics of the transfers described above. The post-injection AV given is for stopping at the surface of the Moon and includes 100 m/s for midcourse corrections for all except the ΔV-minimizing 'i-able 1

TRAJECTORY CHARACTERISTICS OF ASSORTED TYPES OF I>UNAI{ TRANSFER

Type of Transfer	Inject ion C_3 (km^2/s^2)	Post-Inj. AV (m/s)	Longitude of Approach (deg)	Sun-Moon-Probe Angle (deg)	Transfer Time (days)	Max. Earth Distance (km)
Direct	> -2.(I	>2604	-270	arbitrary	-5	400000
1<11)1.	-1.7	2581	-270	arbitrary	-30	400000
Backflip	-1.7	2604	-270	arbitrary	-20	400000
Biparabolic	-1.4	2511	-90	arbitrary	.	∞
WSB	-1.4	2441	-180	-45 or -225	>75	1500000
Interior WSB	-1.4	2441	-o	-45 or -225	>100	1500000
ΔV-Minimizing	-2.9	2475	arb.	arbitrary	>150	450000
Best ΔV-minimizing	-2,9	2372	arb.	arbitrary	>150	450000

ARRIVAL OPTIONS

The arrival descent strategy is governed by two major choices: firstly, a hardware choice whether to use a solid stage to remove most of the Moon-relative velocity, and secondly, a trajectory choice whether to descend directly to the surface or to aim to go around the Moon with a perilune a few kilometers above the surface but using engines to slow down and land around perilune.

With respect to the first choice (of hardware) a liquid propulsion subsystem will be required on the delivered spacecraft in any case, since orbit determination errors combined with solid rocket performance errors force a solid burn ending at a safe altitude many kilometers above the surface. Thus the final descent will have to be handled by other means of on-board propulsion. This means a throttleable liquid propulsion subsystem, which can also be used for attitude control during the solid motor burn. Note that if a solid stage is used the liquid propulsion subsystem would be significantly smaller than one needed to remove all the arrival velocity. There is also a performance gain due to staging.

With respect to the second choice (of trajectory) an approach which has a positive altitude for perilune with horizontal braking at perilune has several characteristics which are different than for the direct descent. It allows a landing on the opposite side of the Moon from the approach direction so that, for example, a WSB transfer could have a landing on the near side of the Moon instead of on the far side. Since the braking would be done horizontally instead of vertically the gravity losses should be much lower than for a direct descent if liquid engines are used (a solid motor burn is sufficiently close to an impulse that gravity losses are very small in either case). Finally, since the braking uncertainty would be horizontal instead of vertical it might be possible to aim for a lower braking altitude, thus reducing the final descent AV required and further increasing the landed mass. On the other hand, this means that the location of the final landing is less well controlled and that the final descent might have to be designed to contend with greater sideways velocities than are likely for a direct descent.

Surveyor-type Delivery

One major advantage of using a solid motor to brake a direct descent is that we know this approach works -- - the Surveyor series of spacecraft successfully used this approach to land on the Moon. Table 2-shows the analysis to calculate the landed mass using a solid stage on a direct descent for selected types of transfer launched with the Taurus/STAR 37xfp and the Med-lite launch vehicles. (The characteristics of the Med-lite were taken from the NASA Request for Proposal; this is quite comparable to the proposed enhanced Delta-lite.) The transfer types analyzed were the worst, best, and an intermediate type of interest from ~'able 1. Arrival at the Moon was modeled closely on the Surveyor arrival strategy: a solid rocket motor would provide the main braking thrust, augmented by liquid vernier engines for balance and control; the solid would burn out at an altitude of 5 to 15 km and then be ejected. The spacecraft would then fall to a point on a predetermined descent curve where the vernier engines under autonomous radar control would take the spacecraft down to a soft landing on the surface. With this strategy, a spacecraft launched by a Taurus/STAR 37xfp would need a STAR 24 for braking at arrival and a spacecraft launched by a Med-lite would need an extended STAR 27 or an offloaded STAR 30. The assumptions made in this mass analysis were as follows:

- an adapter for the spacecraft would be connected to the launch vehicle and would take 1% of the injected mass (the performance cost of the Payload Attach Fitting has been included in calculating the capabilities of the launch vehicles)

- the inerts for the solid motor used to brake the arrival would take 10% of the propellant mass of the arrival for the motor itself plus 3% of the propellant mass for an adapter

- safing and arming hardware for the solid motor would be 10 kg for a STAR 24 and 15 kg for a STAR 27 or STAR 30

- the effective lsp for the arrival braking would be 288 s; the Isp for the vernier engines would be 308 s

- gravity and steering loss for a vertical braking descent would be 10/. of the braking AV

- the AV needed for the final descent is for a high-altitude braking maneuver and is taken from (Surveyor, 1969)

Liquid Propulsion Descent

If a single medium-sized throttleable liquid propulsion system is used, the trajectory for arrival is necessarily the one using horizontal braking around perilune. This is because the gravity losses for a direct descent with the hardware system considered here yield around 20% higher AV than an impulse would require. Gravity losses for the more round-about approach arc a more tolerable 7%. Table 3 shows the analysis for this strategy. Other assumptions used in this analysis were as follows:

- to allow for uncertainties in both the final orbit determination and in the performance of the liquid engine(s), a AV margin of 125 m/s has been included

a single 650 N engine would be used for the spacecraft launched on the Taurus; a spacecraft launched with a Med-lite would usc two such engines characteristics. The other types of transfer have not been studied at all from the navigation point of view; this is especially an issue for WSB transfers, which use a lunar flyby to travel a significant distance from Earth.

On the arrival end, what are the navigation requirements for both the direct arrival and the around-to-perilune arrival? And how do these navigation requirements interact with the approach d irection, where the direct and RID], transfers tend to be in the plane of the sky around the arrival.

The 125 m/s allocated as margin to allow for navigation errors and motor performance uncertainties is itself an educated guess. What is the optimal strategy for dealing with these uncertainties and how much AV margin is really needed?

How do these transfers change as the distance to the Moon changes? This is rather well understood for the direct transfer, but not at all for the other types. This is a daily effect for direct and RIDL transfers, but a monthly effect for the WSB tranfers since they are constrained to particular Sun-Earth-Moon geometries at launch.

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Table 2

LANDED MASSES ON THE MOON FOR SELECTED TRANSFER TRAJECTORIES AND LAUNCH VEHICLES FOR A SURVEYOR-TYPE APPROACH.

(Units used in the table are km^2/s^2 for C3, m/s for ΔV, and kg for mass.)

	A	B	C	D	E	F	G
1		Taurus / STAR37xfp?xfp			Med-lite		
2		Direct	WSB	Minimizing	Direct	WSB	Minimizing
3	C3	-2.00	-1.40	-2.90	-2.00	-1.40	-2.90
4	injected mass	340.0	336.0	347.0	615.0	606.0	628.0
5	adapter (1%)	3.4	3.4	3.5	6.2	6.1	6.3
6	net inj. mass	336.6	332.6	343.5	608.8	599.9	621.7
7	midcrs. det DV	0.0	0.0	70.0	0.0	0.0	70.0
8	midcrs. stat DV	100.0	100.0	50.0	100.0	100.0	50.0
9	midcourse DV	100.0	100.0	120.0	100.0	100.0	120.0
10	midcrse. prop	11.0	10.8	13.4	19.8	19.5	24.2
11	arrival mass	325.6	321.8	330.1	589.0	580.4	597.5
12	arrival vel	2504.0	2341.0	2327.0	2504.0	2341.0	2327.0
13	gravity loss		23.4	23.3	25.0	23.4	23.3
14	arrival DV	2529.0	2364.4	2350.3	2529.0	2364.4	2350.3
15	arrival op	192.6	182.5	186.5	348.5	329.1	337.5
16	solid stage	35.0	33.7	34.2	60.3	57.8	58.9
17	descent mass	98.0	105.6	109.4	180.3	193.5	201.1
18	descent DV	375.0	375.0	375.0	375.0	375.0	375.0
19	descent prop	11.4	12.3	12.8	21.0	22.6	23.5
20	landed mass	86.5	93.3	96.6	159.2	170.9	177.6
21	prop subsys	20.0	20.0	20.0	20.0	20.0	20.0
22	net landed mass	66.5	73.3	76.6	139.2	150.9	157.6
23							
24	post launch DV	3004.0	2839.4	2845.3	3004.0	2839.4	2845.3
25	bipropellant	22.4	23.2	26.2	40.9	42.1	47.7
26	full solid stage	227.7	216.2	220.7	408.8	386.9	396.4

Table 3

LANDED MASSES ON THE MOON FOR SELECTED TRANSFER TRAJECTORIES AND LAUNCH VEHICLES FOR A LIQUID PROPULSION ARRIVAL STRATEGY.

(Units used in the table are km^2/s^2 for C3, m/s for ΔV, and kg for mass.)

	A	B	C	D	E	F	G
1		Taurus / STAR 37xfp				Med-lite	
2		Direct	WSB	Minimizing	Direct	WSB	Minimizing
3	C3	-2.00	-1.40	-?.90	-2.00	-1.40	-2.90
4	injected mass	340.0	336.0	347.0	615.0	606.0	628.0
5	adapter (1%)	3.4	3.4	3.5	6.2	6.1	6.3
6	net inj. mass	336.6	332.6	343.5	608.8	599.9	621.7
7	midcrs. det DV	0.0	0.0	70.0	0.0	0.0	70.0
8	midcrs. stat DV	100.0	100.0	50.0	100.0	100.0	50.0
9	midcourse DV	100.0	100.0	120.0	100.0	100.0	120.0
10	midcrse. prop	11.0	10.8	-13.4	19.8	19. s	24.2
11	arrival mass	325.6	321.8	330.1	589. o	580.4	597.5
12	arrival vel	2504.0	2341.0	2327.0	2504.0	2341.0	2327.0
13	gravity loss	175.3	163.9	162.9	175.3	163.9	162.9
14	statistical DV	125.0	125.0	125.0	125.0	125.0	125.0
15	arrival DV	2804.3	2629.9	2614.9	2804.3	2629.9	2614.9
16	arrival prop	188.7	179.0	1 83.0	341. 4	322.9	331.2
17	landed mass	136.9	142.8	1 47..2	247.6	257.5	266.3
18	prop subsys.	40.0	40.0	40.0	50.0	50.0	50.0
19	net landed mass	96.9	102.8	107.2	197.6	207.5	216.3
20							
21	post launch DV	2904.3	2729.9	2734.9	2904.3	2729.9	2734.9
22	bipropellant	199.7	189.9	196.4	361.2	342.4	3s5.4

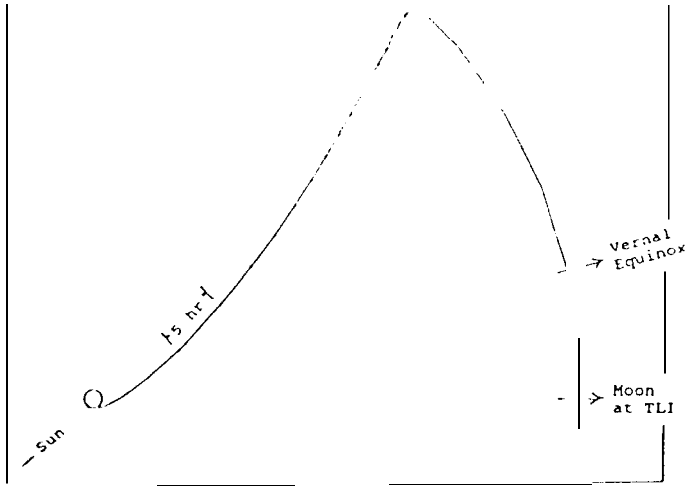

Figure 1. A Direct Transfer shown m inertial coordinates (Ridenoure et al., 1991).

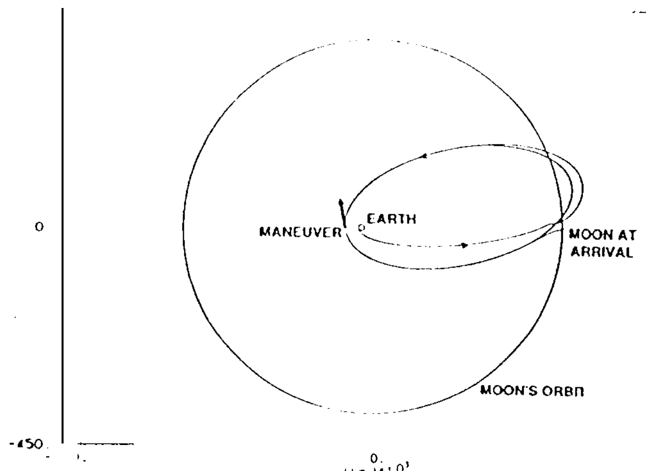

Figure 2. A RIDL Transfer shown ininertial coordinates (Sweetser, 1993a),

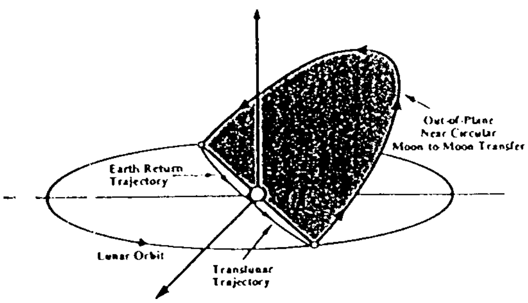

Figure 3 A Backflip Transfer shown in inertial coordinates (Uphoff and Crouch, 1993)

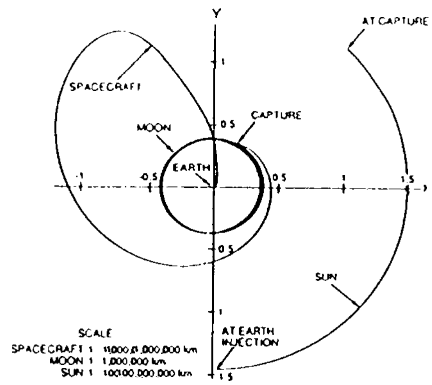

Figure 4. The Belbruno - Miller Transfer (the prototypical Strange Transfer), shown in inertial coordinates (Miller and Belbruno, 1991)

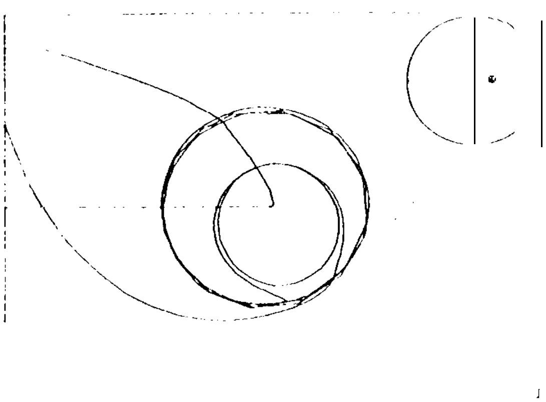

Figure 5 .4 Charmed Transfer, shown in rotating coordinates with the Earth Sun line fixed The B-plane diagram in the corner shows the aimpoint of the first lunar flyby

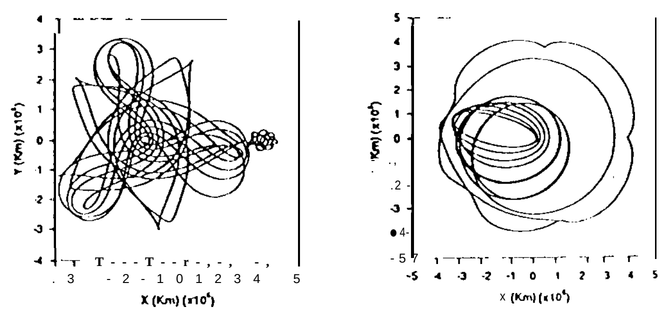

Figure 1. Earth-to-Moon Trajectory Shown in the Rotating Frame

Figure 2. Earth-to-Moon Trajectory Shown in the Inertial Frame

Figure 6. A Minimizing Transfer (Pernicka et al 1994)